NORTHEAST RADIO OBSERVATORY CORPORATION

HAYSTACK OBSERVATORY

WESTFORD, MASSACHUSETTS 01886

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FINAL PROGRESS REPORT

RADAR STUDIES OF THE PLANETS

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R.P. Ingalls
G.H. Pettengill
A.E.E. Rogers
P.B. Sebring (Editor)
I.I. Shapiro

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RADAR STUDIES OF THE PLANETS

1 July 1973 - 30 June 1974

For the past several years NASA has sponsored at Haystack Observatory a program of X-band (3.8 cm) radar investigations of the moon and nearer planets. In many cases, results complement and extend those obtained at the JPL Goldstone facility (S-band) and at Arecibo Observatory, which operates at UHF. Summaries of the work have been presented as part of each issue of the Semi-annual Report of the Haystack Observatory, together with a listing of publications. This is the final progress report on the planetary work under Grant NGR-22-174-003.

I. Summary of Past Work

The radar measurements phase of the lunar studies involving reflectivity and topographic mapping of the visible lunar surface was ended in December 1972, but studies of the data and production of maps have continued. This work was supported by Manned Spacecraft Center, Houston.

Topographic mapping of the equatorial regions of Mars has been carried out during the period of each opposition since that of 1967. The method comprised extended precise travel time measurements to a small area centered on the subradar point. As measurements continued, planetary motions caused this point to sweep out extensive areas in both latitude and longitude permitting the development of a fairly extensive topographical map in the equatorial region.

Radar observations of Mercury and Venus have also been made over the past few years. Refinements of planetary motions, reflectivity maps and determinations of rotation rates have resulted. A "fourth test" of general relativity has also been possible based upon observations of excess echo delay when the ray-path passes near the sun around superior conjunctions. Topographic measurements have also been made, and, in the case of Venus, reflectivity maps have been prepared from data gathered with an X-band radar interferometer composed of Haystack and the nearby "Westford" 60-ft antenna operated by Haystack.

For convenience, Appendix I presents a list of publications resulting from the planetary radar work under this program.

II. Mars

The earlier part of FY74 saw intensive concentration on radar observations of the planet Mars. During September, October and November, 1973, while the planet was near opposition, most data were taken using an effective pulse resolution (baud length) of 6 μsec. The data-taking program consisted of an improved version of one developed in 1971, but which has now been adapted to use a new hardware signal decoder developed under this program. In this way, the total observing window has been increased to 84 μsec. Coupled with the use of an ephemeris in which subradar surface topography has been modeled, this enlarged window has greatly expedited the taking of data, since standard values for the positioning of the window could be used throughout the observations.

Many of the observations during this period corresponded to locations on the surface of Mars observed in 1971. These so-called "closure points" are particularly valuable for determining the orbit of Mars (and Earth), and it was gratifying to note residuals from the ephemeris (prepared from 1971 and earlier data) not exceeding a few microseconds for the new closure data. There are also pairs of closure points lying entirely in the 1973 data span as well. Comparison of the two sets of ranging data obtained simultaneously at Haystack and Arecibo (and also at Goldstone, although those data have not yet been made available to us) also indicate excellent agreement between the two sites, to at least 0.5 μsec, in the measurements of round-trip flight times.

The track of the sub-radar point in 1973 did not extend north of about -14° latitude, and thus no new coverage in latitude is available as compared to earlier years. The 1973 data have, however, greatly extended the coverage in longitude near the southerly limit of the Martian tropics.

Reduction of the simultaneous observations to determine surface scattering properties as a function of wavelength is well underway. The major difference between the new analyses and those carried out in 1971 is that the scattering properties of a small surface element are now being calculated using data at several different observed angles of incidence instead of only one. Since data from a number of different runs, occasionally on different dates, must be combined in the analysis, corrections for changes in operating characteristics must be carried out meticulously if systematic errors are to be avoided. Preliminary test reductions indicate that these systematic errors can, in fact, be troublesome. In most cases there is enough redundancy that the flagrantly offending runs can be identified, however, and removed from the analysis.

The later part of the period was spent entirely in data processing. The 1973 Haystack scattering and topographic data for Mars have been placed in the same format as those obtained at Arecibo in order to facilitate cross comparison, with the objective of determining consistency (topography) and possible wavelength dependence (scattering law). The actual comparisons will be carried out under a separate NASA Grant (NGR 22-009-672) held by G. Pettengill at M.I.T., and continuing into 1975.

G. H. Pettengill
R. P. Ingalls

III. Mercury

Intensive topographic radar observations of Mercury were performed during the July 1973 close approach, using the 24-microsecond pulse mode. This series covered almost the same subradar region as the July-August 1972 observations previously reported. Several other sets of range delay measurements were performed in the November 1973 period.

All Mercury topographic observations of 1971 through 1973 have now been reduced using a common ephemeris, and the results are shown in Figures 1 and 2. Longitude resolution is about 1°, whereas the latitude resolution, as determined by the 24-μsec pulse width, extends ± 2° about the apparent rotation equator (though the scattering law weights the data heavily toward the center of that path).

There appears to be a total height variation of some 4 km. evident over this rather limited sample of latitude and longitude coverage. Local height variations seem limited to about 2 km. in these observations. Although not evident directly from these plots, some areas appeared rough on a medium scale, i.e., mountainous, resulting in a rather erratic determination of height. The regions near 50° and 160° longitude in the July 1973 results are typical of this phenomenon.

Some regions are well behaved in the sense of giving repeatable topographic results. The local dips at 230° in the 1971 data, at 205° in the 1972 data, and 245° in the 1973 data appear to be real in this sense, representing 1 km lower regions. Similarly, the local peaks at 195° and 225° in 1971 and 220° in 1972 are also repeated. The three "spring" passes are at considerably different latitudes and cannot be expected to repeat in a small-scale sense for the three years.

The larger-scale planetary height variations do appear to repeat in both plots as expected. Analysis of the amplitude variations along these height profiles is currently in progress, with a view to determining scattering law and medium-scale topographic variations not resolved by the direct height determinations.

R.P. Ingalls

IV. Venus

Range delay measurements were resumed in August 1973 and continued through the January 1974 close approach, terminating in March 1974. Observations of the region near 285° longitude made in mid-December exhibited local topographic variations of the order of 2 km. This region has previously been observed in reflectivity mapping experiments as a reflection feature identified as Haystack V.*

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* A.E.E. Rogers et al, Icarus 21, 237 (1974).

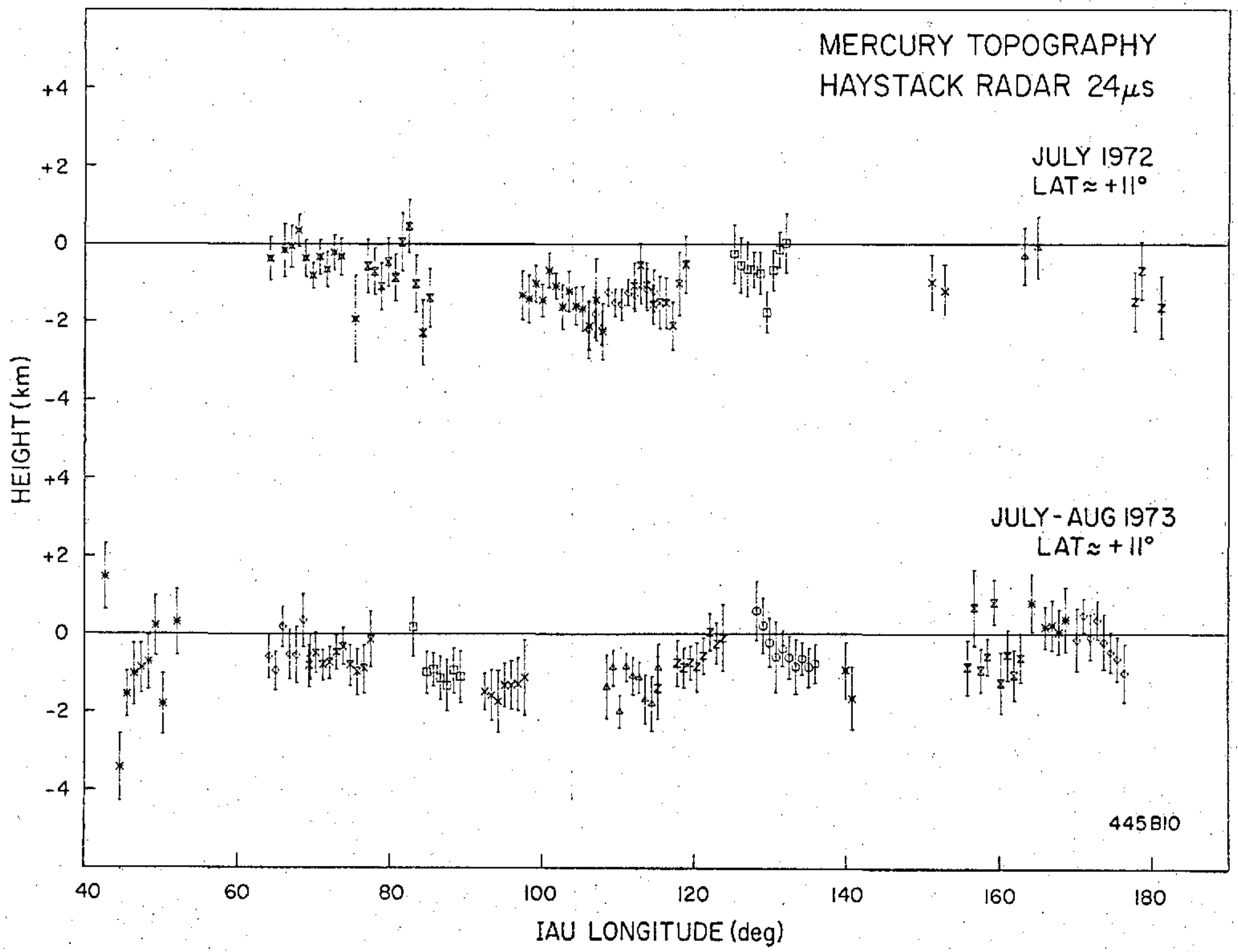

FIG. 1 Mercury topographic profiles from the "summer" close approaches of 1972 and 1973. A common ephemeris (PEP 445B10) was used to remove planetary orbit delay. Each symbol is for an independent observation. Error bars are formal one sigma noise estimates. Coverage in longitude is derived from frequency resolution within an observation.

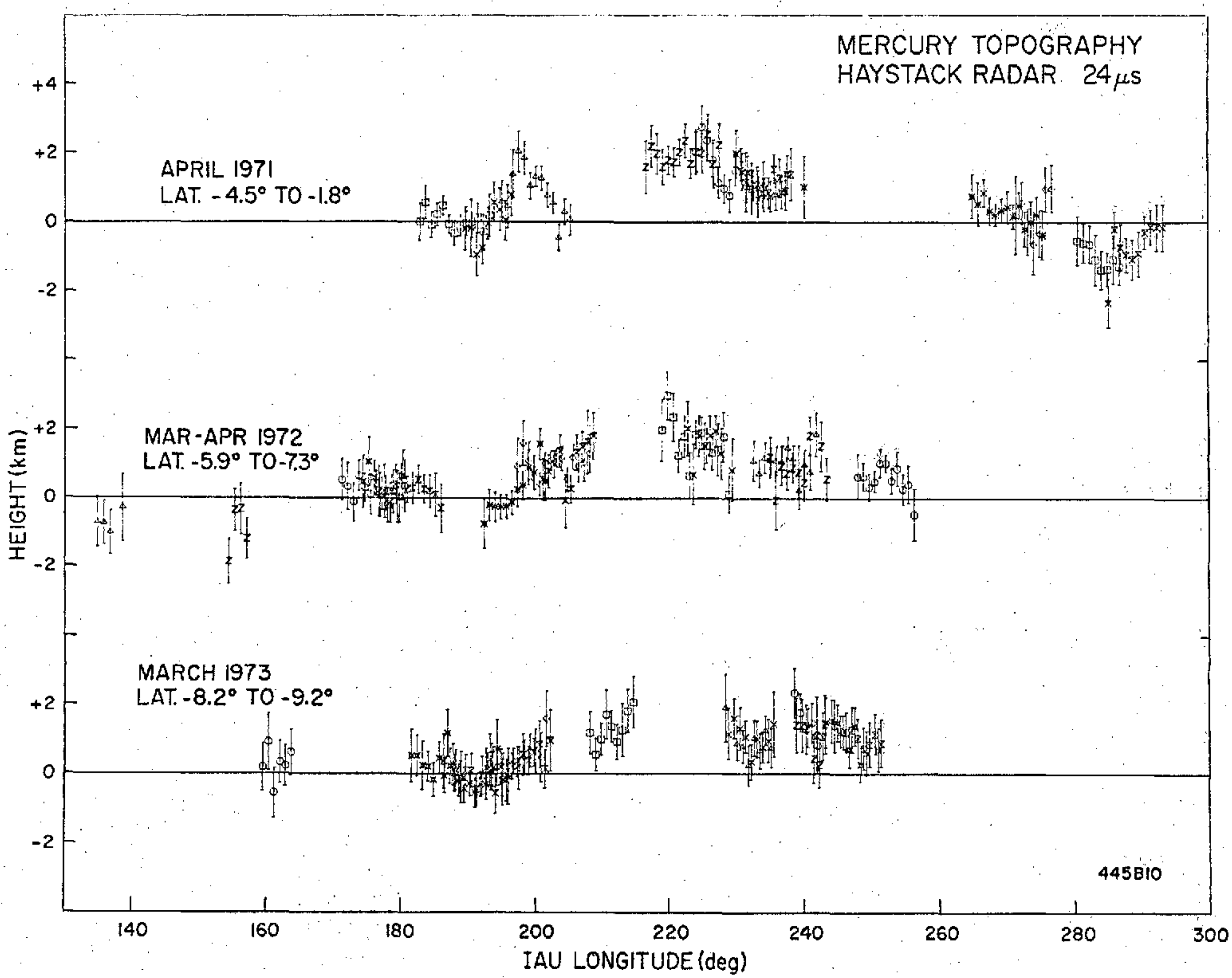

FIG. 2 Mercury topographic profiles from the "spring" close approaches of 1971, 1972, and 1973. Each symbol covers an independent observation but in many cases two observations were made on the same day providing overlap confirmation.

The results of Venus topographic observations are being analyzed by procedures similar to those producing the Mercury results described above. Because of the large volume of data due to the high resolution obtained near close approach, the Venus data analysis is not yet complete. However, the relatively coarse resolution 24-microsecond data have been reduced, and the results from 1967 through 1972 are shown in Figure 3. These observations are primarily useful for regions away from the close approach longitude, where the signal-to-noise ratio limits resolution. Finer grain modes were used in the 1970-71 and 1972 passes and can be expected to provide more accurate data in the 280° to 340° longitude regions.

Venus obviously exhibits more topographic variation than Mercury, exhibiting the 5-km spread evident in the plots. A number of interesting regions are apparent. The high point of the planetary equatorial region is near 90° longitude. The rather erratic height profiles obtained here show this to be a rather rough region on the horizontal scale of 100 to 1000 km.

Similarly, the locally elevated regions near 285° (1972) and 295° (1969 and 1970) are associated with reflection map features, Haystack V and IV respectively*. The rather evident scatter of points in the close approach data of 1970 and 1972 (280° to 340°) is due in part to frequency errors in the profile reduction. The first order effect of such a frequency error is a tilt in the topographic profile. This effect, unfortunately, is maximized here by the small limb-to-limb frequency spread of the planet at inferior conjunction. A second contributing factor to the scatter is the rather large resolution cell of 3.6 km in range delay inherent in the 24 microsecond mode, which results in the weighting of a considerable latitude spread. This scatter is being reduced considerably by work currently in progress, where the 24-microsecond data are being refined in conjunction with 10- and 4-microsecond resolution data.

R.P. Ingalls

V. Saturn's Rings

An attempt was made to observe the rings of Saturn in four observations from 5 to 8 November. There was no echo obtained. The experiment itself ran fairly smoothly in spite of the unusual equipment setup using the digital correlator normally used for radio spectrometry to process the radar signal echo. The transmitter was frequency-shift modulated and the radar timer was used to synchronize the correlator for the doppler shift of predicted echo modulation.

The negative result has allowed us to put an upper limit for radar scattering from Saturn's rings at X-band which is about twice as large as

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* same reference as preceding. See also 15 July 1973 Semiannual Report, pages III-4,5.

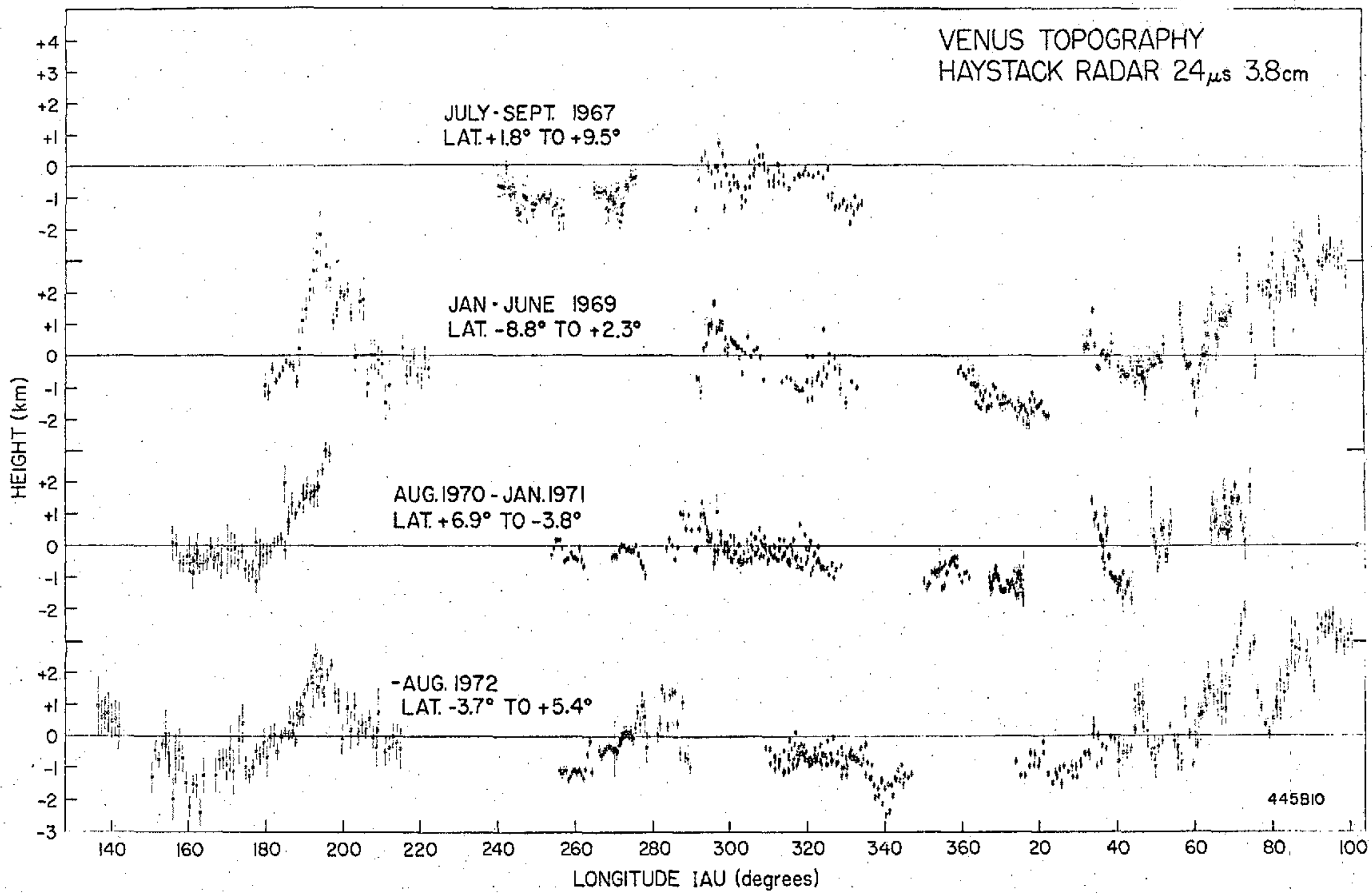

FIG. 3 Venus topographic profiles from 24-microsecond data summarized from 1967 through 1972. Common ephemeris (PEP 445B10) was used to remove planetary orbit delay. High accuracy data obtained near close approach (280-340°) is subject to further refinement.

that actually observed at S-band (by R.M. Goldstein using JPL's 210' "Mars" antenna). Thus, the scattering from the rings cannot be simple Rayleigh $\sim\lambda^{-4}$, and we know that the particles seen by radar at S-band must be of the order of a few centimeters in diameter, or larger.

G. H. Pettengill

VI. Comet Kohoutek

On 12 January 1974, an attempt was made to observe radar echoes from the comet Kohoutek. The Haystack Observatory radar system transmitted a signal at a radio frequency of 7840 MHz ($\lambda \approx 3.8$ cm); about 2 minutes before the echo was expected, the system was reconfigured for reception. The relevant parameters of the radar system were as follows:

Radar frequency:	$f = 7840$
Radar wavelength:	$\lambda \approx 3.8$ cm
Effective antenna area:	$A \approx 470$ m^2
Transmitted power:	$P \approx 200$ kw
System temperature:	$T \approx 50°$K
Integration time for echo:	$t \approx 5 \times 10^3$ sec
Earth-comet distance:	$R \approx 1.24 \times 10^{11}$ m
Ephemeris round-trip-time-of-flight for echo received at 16:00 UT:	$\tau \approx 812.246$ sec
Ephemeris Doppler shift for echo received at 16:00 UT:	$\Delta f \approx 498{,}938$ Hz

The transmit/receive cycle, or "run", was repeated several times during the period of visibility of the comet. The results from these runs were "stacked" in accord with the ephemeris we produced from the initial conditions then available for Kohoutek's orbit (B. Marsden, private communication, 1973). Comparison, "noise-only" runs were subtracted before further processing to attempt to remove any slope and "ripple" in the power spectrum that might be caused by the instrumentation.

Since neither the bandwidth nor the center frequency of the radar echo was known precisely, the spectral region within ±33 kHz of the expected frequency of the echo was searched at various resolutions. For the frequency interval within ±925 Hz, the spectral analysis was performed with a 2-Hz resolution, utilizing a multi-bit Fourier technique normally used for planetary radar experiments. For the extended frequency interval, bandwidths of 12 kHz and 66 kHz were searched with resolutions of 0.2 kHz and 1 kHz, respectively. For this latter analysis, we used the one-bit digital autocorrelator normally employed at Haystack for observations of spectral-line emission from the interstellar medium. The procedures used in both analyses were tested thoroughly by observing strong echoes from the planet Venus.

No echo was apparent in any of the spectra obtained from the observations of the comet. We can infer from this result an upper limit on the radar cross section, σ, of the comet by means of the radar equation:

$$\sigma = \frac{4\pi\lambda^2 R^4 kT(S/N)B^{1/2}}{PA^2 t^{1/2}}, \qquad (1)$$

where S/N denotes the signal-to-noise ratio, B the echo bandwidth, and k Boltzmann's constant, while the other quantities are as defined earlier. If we take $(S/N) = 5$, a conservative value, the upper limit on the cross section is 5×10^3 km^2 Hz$^{1/2}$ for the frequency interval of ±925 Hz; however, for the extended frequency interval, this limit must be increased by approximately a factor of two to 10^4 km^2 Hz$^{1/2}$ to account for the clipping correction inherent in the one-bit auto-correlation spectral analysis.

We recognized from the beginning that the sensitivity of the Haystack radar system was insufficient to have detected an echo from the comet nucleus (hard target) were it no larger than the usually accepted estimate of a few tens of kilometers. However, we reasoned that a high-frequency echo might be observed from Rayleigh scattering in the considerably larger comet coma (soft target). Under the assumption that the particles in the coma are much smaller than the wavelength λ of the radio signals, the radar cross section is approximately $4\pi N(2\pi)^4(a^6/\lambda^4)|[m^2-1]/[m^2+2]|^2$, where a is the radius, N the number, and m the complex index of refraction of the particles.

In the absence of a definitive echo, its spectral width and shape are, of course, unknown. However, as an illustrative example, if we assume a flat spectrum of 100-Hz width, then we can conclude that (i) the density of millimeter-sized particles in a coma of diameter 10^4 km must be less than 1 m^{-3} (we ignore the small effects of "shadowing" and the possibility of an anomalously small index of refraction); and (ii) the diameter of the nucleus of the comet, if considered to be a perfectly reflecting solid-body target, must be less than about 250 km.

Eric J. Chaisson
Harvard College Observatory

R.P. Ingalls, A.E.E. Rogers
Haystack Observatory

I.I. Shapiro
M.I.T.

HAYSTACK OBSERVATORY

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